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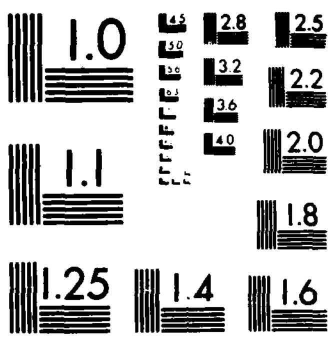

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Development of a Model for Swirling Flows

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The purpose of this project was to develop a second order model for weakly swirling flows. The model was based on a successful model for the buoyancy driven mixed layer of the atmosphere.

In a swirling flow, the swirl sets up a radial pressure gradient. This causes a drop in the axial value of the pressure. As the swirl decays along the axis, the axial pressure rises, creating an adverse pressure gradient. If the swirl is strong enough, this adverse gradient causes flow reversal. A weakly swirling flow is one in which this does not happen. We limit ourselves to weakly swirling flows because they can be computed with parabolic programs, stepping in the axial direction. In addition, models can be simpler, since turbulent transport in the axial direction can be neglected in a weakly swirling flow. A strongly swirling flow must be computed with an elliptic program, and turbulent transport in all directions is important. Strongly swirling flows occur more widely and are more important technologically; weakly swirling flows are regarded as a necessary step on the path to computing strongly swirling flows.

Swirling flows present a challange to the modeler due to the influence of radial turbulent transport on the radial distribution of azimuthal velocity. This is weakly analogous to the effect of density stratification in a flow with gravity. A radial distribution of angular momentum increasing outward will have a stabilizing influence, and will suppress radial transport and reduce the rate of spread of a scalar marker, while a radial distribution of angular momentum decreasing outward will have the opposite effect.

In Lumley (1978) [for references, see Ettestad, 1985] an approach was outlined to the modeling of the buoyantly driven surface mixed layer. Specifically, this approach gave forms for the third moments, responsible for the turbulent transport of the variances and fluxes. Unlike other models in common use, this approach is based on first principles, and should be regarded as an approximation, rather than a model. It introduces no additional constants, and contains nothing adjustable. It is basically a perturbation expansion about a state of equilibrium, for very fine-grained turbulence. Inhomogeneity is taken to be the disturbing influence which perturbs the turbulence away from a Gaussian equilibrium state. The structure of the approximation is similar to non-equilibrium thermodynamics of a mixture, in which fluxes of one species are caused by gradients of the others. Here, the role of the species is played by the variances and fluxes. This approach has been extremely successful in the atmospheric case, giving results for the third moments within experimental error.

In Lumley (1981) we outlined an approach to swirling flow constructed by analogy with the buoyant case. In this project, we wished to implement this approach, ultimately calculating one or more weakiy swirling flows.

This project has served as the Ph. D. Thesis of David Ettestad, and the work done is described there (Ettestad, 1985). The implementation of the approach outlined in Lumley (1981) turned out to be not as straightforward as had been thought. Ettestad discovered a number of minor errors in the models that had been proposed by Lumley (1978); correction of the error usually resulted in a generalization of the model. In Lumley (1981) the so-called narrow-gap approximation had been made in certain circumstances - in effect, the assumption that the radius of curvature was large relative to the local length scale. This, of course, was not expected to be true close to the axis of curvature, but it was not expected that it would be serious. In the event, it was. We tested the model on a swirling jet, which is well-documented. It was necessary to develop a new program which computed the jet on conical coordinates, in normalized form, in effect introducing a similarity transformation; if the flow were self-similar (which is not expected) it would be invariant in these coordinates. Previous attempts to compute this flow had met with great difficulty in predicting certain components of the Reynolds stress responsible for the very rapid spread of the jet immediately after leaving the orifice. The failure to predict this relatively brief phase of the jet development left a deficit in radial growth which persisted indefinitely.

Ettestad had the same difficulty, but finally resolved it by a clever modification to the dissipation equation, which we were able to motivate physically *a posteriori*.

In the end Ettestad was entirely successful in modeling the weakly swirling jet. More important, the corrections, modifications and additions he made to the model are of general utility, and shed light on the construction of models for use in many other circumstances, and on the behavior of models in general. We are in the process of preparing several more papers based on Ettestad's thesis.

Publications Directly Related to this Grant

Ettestad, D. and Lumley, J. L. 1985. Parameterization of turbulent transport in swirling flows I: Theoretical considerations. In *Turbulent Shear Flows 4* , Eds. L. J. S. Bradbury, F. Durst, B. E. Launder, F. W,. Schmidt and J. H. Whitelaw, pp. 87-101. Berlin/Heidelberg: Springer.

Lumley, J. L., Ettestad, D. J. and Morel, P. 1986. Modeling the effect of buoyancy and rotation on turbulence. In *Proceedings: International Symposium on Refined Flow Modeling and Turbulence Measurements*. (ed. C. J. Chen). Amsterdam: Elsevier. In Press.

Ettestad, D. J. 1985. *A Second Order Model of a Swirling Turbulent Jet* . Ph. D. Thesis, Cornell University. Also Sibley School of Mechanical and Aerospace Engineering Report No. FDA-85-06.

Presentations directly related to this Grant

Modeling the effect of buoyancy and rotation on turbulence. EUROMECH 180 Conference, University of Karlsruhe, W. Germany, July 4-6, 1984.

Modeling the effect of buoyancy and rotation on turbulence. International Symposium on Refined Flow Modeling and Turbulence Measurements. The University of Iowa, Iowa City, Iowa, 16-18 September 1985.

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